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Utilisation of symmetrical components in a communication-based protection for loop MV feeders with variable short-circuit power

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Abstract: Variability of the available short-circuit power also implies variation of the fault level, which can potentially cause several protection problems in the electric networks. In this study, a novel protection method that is insensitive to the fault level changes caused by variable short-circuit power is presented. It relies on utilisation of symmetrical components of the short-circuit currents and on communication between the protection relays. The proposed method addresses the single phase to ground (SPG) faults occurring in directly grounded distribution networks, with focus on closed-loop medium voltage (MV) feeders. Case studies are presented, which demonstrate that the proposed protection scheme is capable of effectively detecting the SPG faults in closed-loop feeders with variable short-circuit power.

1 Introduction

In general, the distribution networks comprise radial feeders supplied from a single utility source [1]. In this arrangement, the current flow is unidirectional and protection against the short-circuit faults is realised typically by overcurrent (OC) relays [1], but an electric fault could cause a power outage for all loads placed downstream the fault location [2]. In order to address this drawback, some distribution networks comprise loop feeders, so that no consumer will be out of service in the event of a single fault within the feeder [3]. However, in a closed-loop feeder the current flow is bidirectional and the conventional OC protection needs to be upgraded in order to provide proper protection against the electric faults [2, 3].

Regardless of the type of feeder involved in a distribution network, its protection system is challenged by variability of the available short-circuit power, as the short-circuit currents are also variable in this situation [4]. With the advance of distributed generation, variability of the short-circuit power is not uncommon nowadays [5] and the protection system needs to operate correctly even in such conditions. It is well known that the traditional OC relays are not suitable in these conditions, as they could experience longer tripping times, loss of coordination and other protection issues [4, 5]. In order to mitigate some of the protection problems mentioned above, a new protection scheme is proposed in [5] for radial MV feeders with variable short-circuit currents. The proposed protection scheme is effective against SPG faults occurring in directly grounded distribution feeders and relies on the evaluation of the ratio between the zero sequence and positive sequence of the fault current. More precisely, the SPG fault in a radial feeder is indicated by a non-zero magnitude of this ratio for all relays located upstream of the fault location and precisely this information is used in [5] to clear the faulted section of the feeder. As a continuation of the work presented in [5], the proposed protection scheme is improved so that it can also be applied in closed-loop feeders. Therefore, this paper presents a new communication-based protection scheme for loop MV feeders with variable short-circuit power.

The protection scheme proposed in this paper has several benefits over conventional OC protection. It is insensitive to fault level changes, so it only needs a single set of settings for its relays for a wide range of network conditions and it does not require a prior knowledge of the rated or fault currents in the circuit that needs to be protected. Moreover, the proposed protection scheme allows for normally-open-loop feeders to be closed without the need of voltage transformers, as in the case of directional OC relays [6] or additional current transformers (CTs). The newly developed protection scheme has been tested in a closed-loop MV feeder with variable short-circuit power using PSCAD and the simulation results demonstrate its effectiveness in these conditions.

The remaining of this paper is structured as follows. Sections 2 and 3 present the theoretical background of the proposed method of protection. In Section 2, the SPG fault is analysed using the method of symmetrical components in a distribution feeder and based on this analysis the new method of protection is described in Section 3. In Section 4, some case studies are presented and PSCAD is used for simulating various fault conditions to validate the performance of the proposed protection scheme. Section 5 concludes this paper with some final remarks.

2 Fault analysis

Analysis of the SPG fault seeks to determine the symmetrical components of the fault currents, as measured by the CTs in a loop feeder. It should be noted that only these currents are available for the protection system, so only their equivalent sequence components present interest in this paper. Once these quantities are determined, the ratio between the current zero sequence and current positive sequence is calculated in the eventuality of a closed-loop, respectively, open-loop (radial) feeder. The objective is to determine the difference between these two scenarios, as noticed by the aforementioned ratio and based on them to adapt the method of protection proposed in [5] for the case of closed-loop feeders.

2.1 Loop feeder

Fig. 1 presents a simplified electric feeder used for analysis of the SPG fault. The feeder consists of four bus bars and three loads and is supplied from both ends by a three-phase power source with a solid-earthed neutral. The loads are balanced and connected to the network in a delta configuration, resembling in this sense the primary winding of a typical distribution transformer. The bus bars are interconnected by four cables, denoted as Cx, where x is the tag

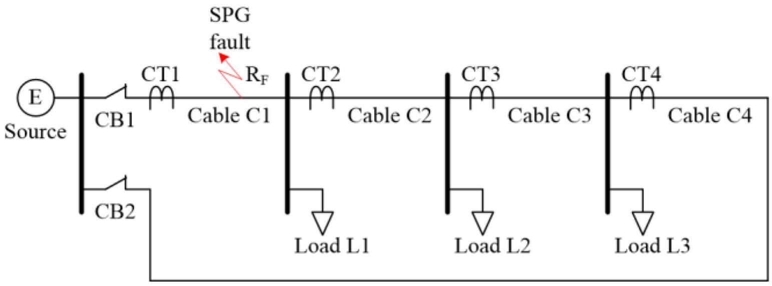

Fig. 1 *Loop feeder in SPG fault conditions*

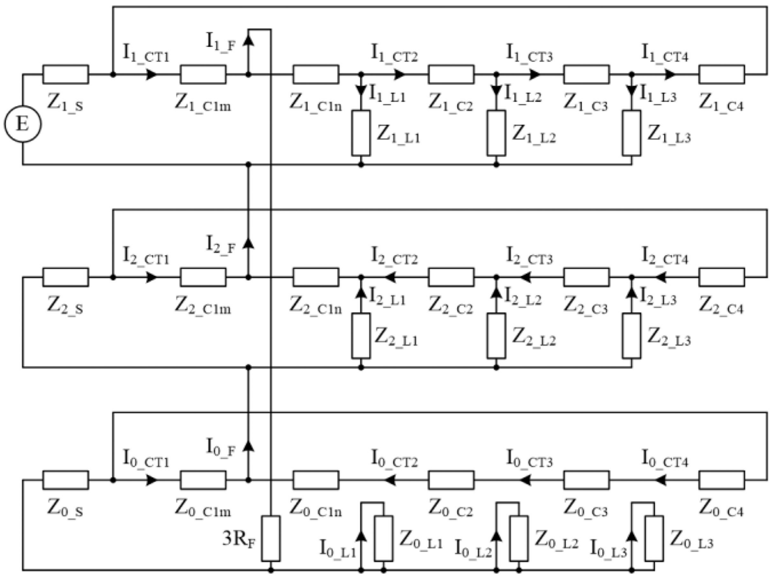

Fig. 2 *Equivalent sequence diagram of the loop feeder during SPG fault*

of the cable. Monitoring of the feeder is realised for protection purposes by four sets of CTs, labelled as CTx, where x is the tag of the CT. The loop feeder can become radial by opening of either circuit breaker (CB) CB1 or CB2. The electric loads are labelled as $L1$, $L2$ and $L3$, respectively, while the internal e.m.f. of the power source is denoted as E. A SPG fault with the fault resistance R_F is applied on cable $C1$ and the fault current is fed from both sides of the loop feeder.

Fig. 2 presents the equivalent sequence diagram of the loop feeder described previously and the following notations are used. Z_{0_S}, Z_{1_S}, Z_{2_S} and Z_{0_Lx}, Z_{1_Lx}, Z_{2_Lx} denote the zero, positive and negative-sequence impedances of the source and of the loads respectively. Z_{0_Cx}, Z_{1_Cx}, Z_{2_Cx} are the sequence impedances of cables $C2$, $C3$ and $C4$, while $Z_{0\_C1}m$, $Z_{1\_C1}m$, $Z_{2\_C1}m$, respectively, Z_{0_C1n}, Z_{1_C1n}, Z_{2_C1n} are the sequence impedances of the sections of cable $C1$ located upstream, respectively, downstream to the SPG fault location. I_{1_F}, I_{2_F}, I_{0_F} are symmetrical components of the fault current, I_{1_Lx}, I_{2_Lx}, I_{0_Lx} are symmetrical components of the load currents and I_{1_CTx}, I_{2_CTx}, I_{0_CTx} are symmetrical components of the currents measured by the CTs.

Due to the delta connection, the zero-sequence quantities associated with the loads, namely Z_{0_L1}, Z_{0_L2}, Z_{0_L3}, I_{0_L1}, I_{0_L2} and I_{0_L3} do not influence the feeder currents during the SPG fault [7]. On the contrary, the positive and negative-sequence quantities associated with these loads influence these currents in fault conditions. In this sense, (1)–(4) give the positive-sequence currents seen by each set of CTs, as a function of the fault and load currents

$$I_{1\_CT1} = AI_{1\_L1} + BI_{1\_L2} + CI_{1\_L3} + F_1 I_{1\_F} \tag{1}$$

$$I_{1\_CT2} = -A' I_{1\_L1} + BI_{1\_L2} + CI_{1\_L3} - F_1' I_{1\_F} \tag{2}$$

$$I_{1\_CT3} = -A' I_{1\_L1} - B' I_{1\_L2} + CI_{1\_L3} - F_1' I_{1\_F} \tag{3}$$

$$I_{1\_CT4} = -A' I_{1\_L1} - B' I_{1\_L2} - C' I_{1\_L3} - F_1' I_{1\_F} \tag{4}$$

Factors A, A', B, B', C, C', F_1 and F_1' are given in (5)–(8) as a function of positive-sequence impedances of the electric cables and total feeder impedance, denoted as Z_{1_feeder} and given in (9)

$$A = \frac{Z_{1\_C2} + Z_{1\_C3} + Z_{1\_C4}}{Z_{1\_\text{feeder}}}, \quad A' = 1 - A \tag{5}$$

$$B = \frac{Z_{1\_C3} + Z_{1\_C4}}{Z_{1\_\text{feeder}}}, \quad B' = 1 - B \tag{6}$$

$$C = \frac{Z_{1\_C4}}{Z_{1\_\text{feeder}}}, \quad C' = 1 - C \tag{7}$$

$$F_1 = \frac{Z_{1\_C1n} + Z_{1\_C2} + Z_{1\_C3} + Z_{1\_C4}}{Z_{1\_\text{feeder}}}, \quad F_1' = 1 - F_1 \tag{8}$$

$$Z_{1\_\text{feeder}} = Z_{1\_C1m} + Z_{1\_C1n} + Z_{1\_C2} + Z_{1\_C3} + Z_{1\_C4} \tag{9}$$

These factors determine the distribution of the load and fault currents through different sections of the feeder; therefore they influence the currents seen by the CTs during the fault conditions.

Symmetrical components of the SPG fault currents are given in (10), where Z_0 and Z_2 are the equivalent zero-sequence and negative-sequence impedance, respectively, as seen at the fault location

$$I_{0\_F} = I_{1\_F} = I_{2\_F} = \frac{E}{Z_{1\_S} + FZ_{1\_C1m} + 3R_F + Z_2 + Z_0} \tag{10}$$

Furthermore, the zero-sequence currents seen by the CTs are determined in (11) and (12) as a function of I_{1_F}

$$I_{0\_CT1} = F_0 I_{1\_F} \tag{11}$$

$$I_{0\_CT2} = I_{0\_CT3} = I_{0\_CT4} = -F_0' I_{1\_F} \tag{12}$$

Factors F_0 and F_0' are given in (13) as a function of the equivalent zero-sequence impedances of the cables and total feeder impedance, denoted as Z_{0_feeder} and given in (14)

$$F_0 = \frac{Z_{0\_C1n} + Z_{0\_C2} + Z_{0\_C3} + Z_{0\_C4}}{Z_{0\_\text{feeder}}}, \quad F_0' = 1 - F_0 \tag{13}$$

$$Z_{0\_\text{feeder}} = Z_{0\_C1m} + Z_{0\_C1n} + Z_{0\_C2} + Z_{0\_C3} + Z_{0\_C4} \tag{14}$$

Finally, the ratios between the zero-sequence components and positive-sequence components of the currents seen by each set of CTs are given in the following equations:

$$\frac{I_{0\_CT1}}{I_{1\_CT1}} = \frac{F0 I_{1\_F}}{AI_{1\_L1} + BI_{1\_L2} + CI_{1\_L3} + F_1 I_{1\_F}} \tag{15}$$

$$\frac{I_{0\_CT2}}{I_{1\_CT2}} = \frac{-F'_0 I_{1\_F}}{-A' I_{1\_L1} + BI_{1\_L2} + CI_{1\_L3} - F'_1 I_{1\_F}} \tag{16}$$

$$\frac{I_{0\_CT3}}{I_{1\_CT3}} = \frac{-F'_0 I_{1\_F}}{-A' I_{1\_L1} - B' I_{1\_L2} + CI_{1\_L3} - F'_1 I_{1\_F}} \tag{17}$$

$$\frac{I_{0\_CT4}}{I_{1\_CT4}} = \frac{-F'_0 I_{1\_F}}{-A' I_{1\_L1} - B' I_{1\_L2} - C' I_{I\_L3} - F'_1 I_{1\_F}} \tag{18}$$

These ratios are complex numbers and their evaluation could provide valuable information for the protection system. In healthy conditions, the magnitude of these ratios is zero, but during the SPG fault their magnitudes increase significantly. Furthermore, assuming that $F_1 = F_0$, which is typically true [8], is clear that the magnitudes of I_{0_CT1}/I_{1_CT1} and I_{0_CT4}/I_{1_CT4} cannot exceed 1 even in fault conditions. However, the same cannot be said about I_{0_CT2}/I_{1_CT2} and I_{0_CT3}/I_{1_CT3}, as their magnitudes could exceed 1, depending on the value of the factors A, B, C and F. More importantly, there is no relation between the location of the SPG fault in the closed-loop feeder (e.g. in between $CT1$ and $CT2$ in this analysis) and the magnitudes of the examined ratios. Therefore, by observing these ratios in a loop feeder, only the presence of the SPG fault can be indicated, but not its exact location.

2.2 Radial feeder

If $CB2$ is opened, the considered loop feeder becomes radial and the load and fault currents will be supplied from a single direction through $CT1$. In this situation, the mathematical expression of the ratio between the zero-sequence and positive-sequence of the current seen by $CT1$ is given in (19). Again, the magnitude of I_{0_CT1}/I_{1_CT1} is zero only in healthy conditions and it increases significantly during the SPG fault, but it will not exceed 1

$$\frac{I_{0\_CT1}}{I_{1\_CT1}} = \frac{I_{1\_F}}{I_{1\_L1} + I_{1\_L2} + I_{1\_L3} + I_{1\_F}} \tag{19}$$

I_{0_CT2}/I_{1_CT2} and I_{0_CT3}/I_{1_CT3} are zero in both healthy and fault conditions for the considered SPG fault with *CB2* open, as the fault current does not pass through $CT2$ and $CT3$. Also, no current passes through $CT4$ because $CB2$ is open; therefore I_{0_CT4}/I_{1_CT4} is zero in this situation.

If $CB1$ is opened, while $CB2$ is kept closed, the feeder is supplied from the opposite direction through $CT4$. In this situation, no current will pass through $CT1$, while the fault current produced by the considered SPG fault is noticed by all of the other CTs. The ratio between the current zero-sequence and current positive-sequence, as seen by those CTs is given in the following equations:

$$\frac{I_{0\_CT2}}{I_{1\_CT2}} = \frac{-I_{1\_F}}{-I_{1\_L1} - I_{1\_F}} \tag{20}$$

$$\frac{I_{0\_CT3}}{I_{1\_CT3}} = \frac{-I_{1\_F}}{-I_{1\_L1} - I_{1\_L2} - I_{1\_F}} \tag{21}$$

$$\frac{I_{0\_CT4}}{I_{1\_CT4}} = \frac{-I_{1\_F}}{-I_{1\_L1} - I_{1\_L2} - I_{1\_L3} - I_{1\_F}} \tag{22}$$

During the SPG fault, I_{0_CT2}/I_{1_CT2}, I_{0_CT3}/I_{1_CT3} and I_{0_CT4}/I_{1_CT4} are different from zero, but their magnitudes cannot exceed 1 with $CB1$ open, as (20)–(22) indicate. Relations (20)–(22) also indicate that in a radial feeder the closest upstream CT to a SPG fault will notice the highest magnitude of the ratio between the zero-sequence current and positive-sequence current. Indeed, $|I_{0\_CT2}/I_{1\_CT2}| > |I_{0\_CT3}/I_{1\_CT3}| > |I_{0\_CT4}/I_{1\_CT4}|$, as $CT2$ is the closest CT to the location of the analysed SPG fault, followed by $CT3$.

Table 1 summarises analysis of the SPG fault by presenting the possible values of the magnitude of the ratio between the zero-sequence and positive-sequence of the currents seen by the CTs indicated in Fig. 1 for various configurations of the analysed loop feeder.

3 Proposed method of protection

Based on the analysis of SPG faults in Section 2, this section presents a new protection algorithm that is applicable to closed-loop feeders with the aid of communication. As already mentioned, information provided by the magnitude of $I0\_CT1/I1\_CT1$, $I0\_CT2/I1\_CT2$, $I0\_CT3/I1\_CT3$ and $I0\_CT4/I1\_CT4$ allows accurate localisation of the faulted section of the feeder only in radial feeders, while in loop feeders these quantities can indicate only the presence of the SPG fault. Precisely this information is used in this paper to protect a loop feeder using the ratio between the zero sequence and positive sequence of the CTs currents during the fault.

Consequently, this paper proposes that during the SPG fault, the closed-loop feeder is opened at one end, thus becoming radial. In this way, the protection problem of a loop feeder is reduced to the protection of a radial feeder. Then by correlation of the aforementioned ratios using communication, the faulted section of

Table 1 Summary of ratio between the zero-sequence and positive-sequence currents as seen by CTs of the loop feeder shown in Fig. 1

Ratio	Magnitude in SPG fault conditions			Magnitude in absence of SPG fault ($R_F = \infty$)
	Closed-loop feeder	Open-loop *CB*1 open	Open-loop *CB*2 open	
$\frac{I_{0\_CT1}}{I_{1\_CT1}}$	≠ 0, < 1	= 0	≠ 0, < 1	= 0
$\frac{I_{0\_CT2}}{I_{1\_CT2}}$	≠ 0, theoretically no limit	≠ 0, < 1	= 0	= 0
$\frac{I_{0\_CT3}}{I_{1\_CT3}}$	≠ 0, theoretically no limit	≠ 0, < 1	= 0	= 0
$\frac{I_{0\_CT4}}{I_{1\_CT4}}$	≠ 0, < 1	≠ 0, < 1	= 0	= 0

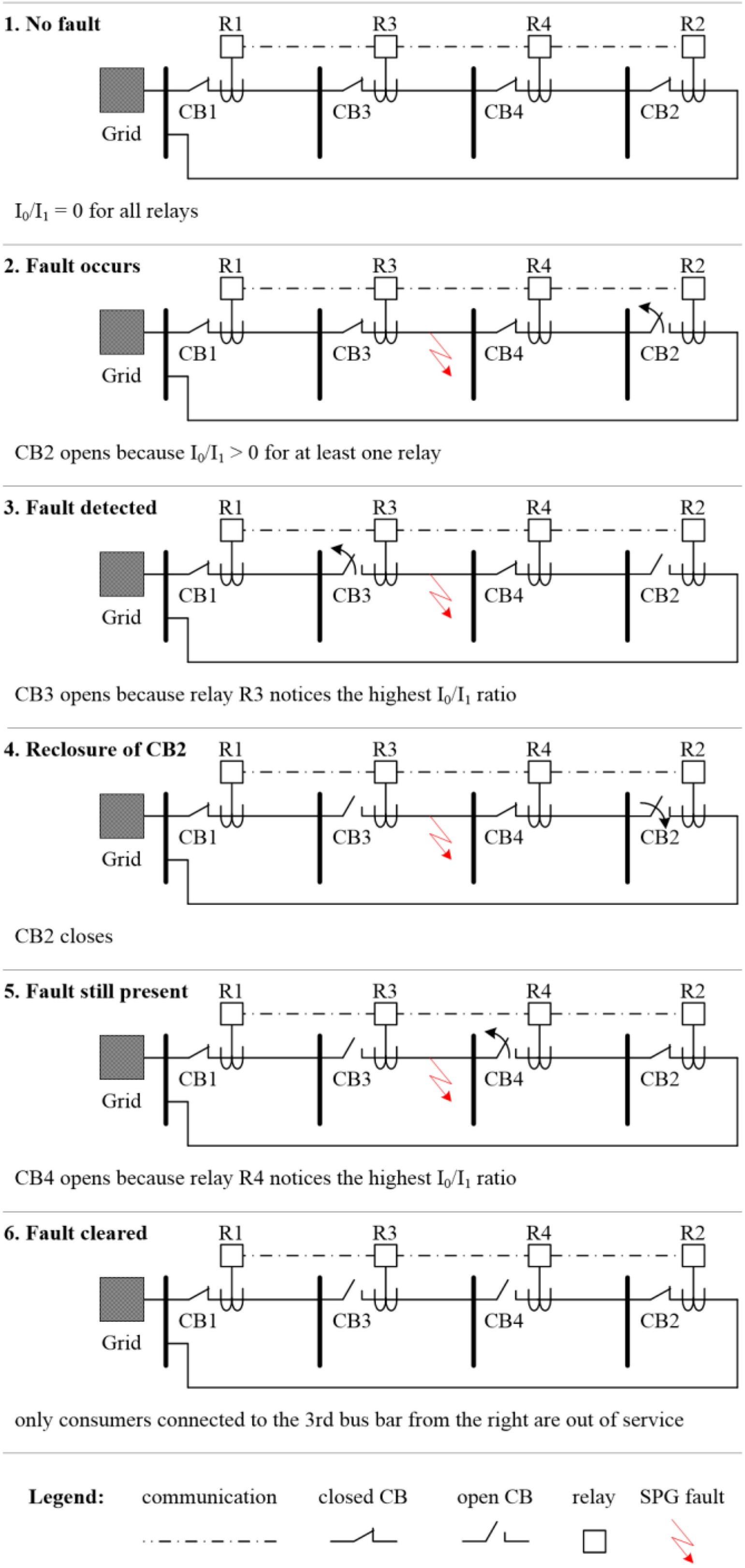

Fig. 3 *Description of the proposed protection algorithm*

the feeder is identified and disconnected by the appropriate CB. When the SPG fault is cleared, the feeder is supplied again from both of its ends, thus ensuring that only the minimum amount of consumers are out of service. The described algorithm of protection is illustrated in Fig. 3 in six steps using the loop feeder shown in Fig. 1. *Rx* denotes the protection relays, where *x* is the tag of the relay, all linked by a communication channel.

Operation of *CB*2 during the fault is similar to the operation of a re-closer, with the observation that in the proposed protection scheme, *CB*2 should stay open long enough to allow detection of the faulted section of the feeder. The time interval between opening and closing of *CB2* depends on communication speed between the relays.

4 Case studies and simulation results

4.1 Description of the test MV loop feeder

Operation of the protection scheme proposed in this paper is demonstrated in a closed-loop MV feeder powered by a utility

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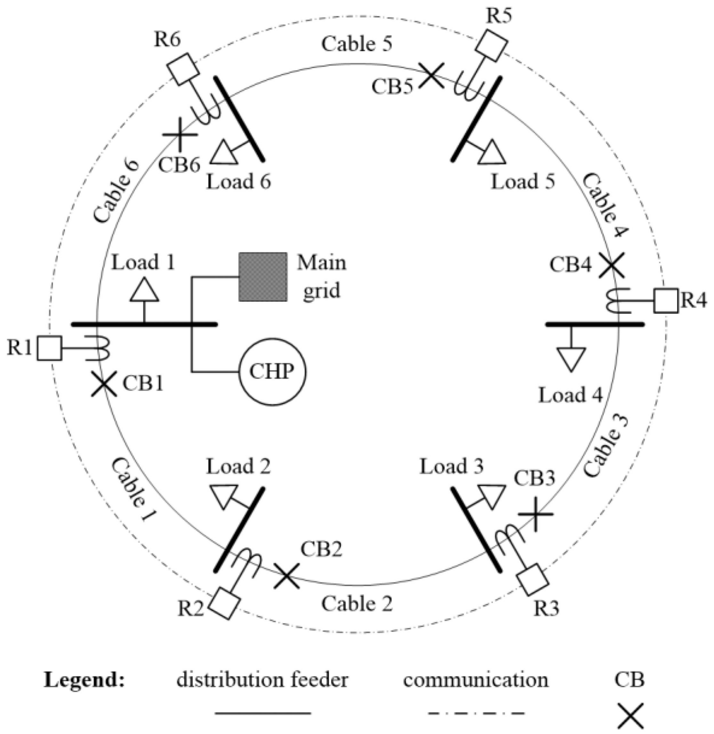

Fig. 4 *Test MV microgrid*

Table 2 Load data

Load	Load 1	Load 2	Load 3	Load 4	Load 5	Load 6
Power, kVA	1200	900	900	1200	900	1500

Table 3 Parameters of the cables

Electric cable	Resistance, mΩ	Inductance, μH	Capacitance, nF
Cable 1	124	294	497
Cable 2	97	158	220
Cable 3	201	248	278
Cable 4	262	188	147
Cable 5	182	99	65
Cable 6	115	180	110

source characterised by variable short-circuit power. In this sense, the protection scheme is implemented using PSCAD in the test MV microgrid illustrated in Fig. 4, operating at a rated voltage of 13.8 kV. The test microgrid consists of six loads tapped on a loop feeder and powered by the main grid or by a 7.5 MVA combined heat and power (CHP) plant. If the main grid is not available, then the test microgrid operates in an islanded mode, supplied by the CHP plant. The main grid is modelled using an ideal voltage source placed behind a 110/13.8 kV transformer with a rated power of 21 MVA. The feeder consists of six cables, modelled using the π-model, while the electric consumers are modelled as constant power loads with a power factor of 0.95. CBs and CTs are assumed to be ideal. The main parameters of the loads and cables are given in Tables 2 and 3, respectively. The CHP plant is modelled as a three-phase synchronous generator driven by an internal combustion engine using the standard models available in PSCAD. Parameters of the CHP plant and of the power transformer are given in [5].

The protection system consists of six relays that are able to transmit their corresponding ratios between the zero-sequence and positive-sequence currents to the other relays and based on the correlation of these ratios to trip the adequate CB. A minimum threshold is defined for the magnitude of the ratio between the zero sequence and positive sequence of the current seen by each relay, below which the ratio is assumed to be zero. In this paper, the threshold is set to 0.2 and its purpose is to avoid a false tripping. When the SPG is detected by a relay, the closed-loop feeder is opened by the opening of *CB*6 and then reclosed after 0.4 s. Also, the tripping of the relays is delayed in simulations by 0.2 s in order to allow a better observation of the ratio between the zero-sequence and positive-sequence currents.

4.2 Operation of the protection system

In this section, the operation of the proposed protection system is examined in both grid-connected and islanded modes of the test MV microgrid. A bolted SPG fault is applied on *phase a* in the middle of *Cable 2* and regardless of the microgrid's operating mode, the faulted section of the feeder should be disconnected by the opening of *CB*2 and *CB*3. The results are presented in Fig. 5 for the grid-connected mode and in Fig. 6 for the islanded mode of the microgrid. In both figures, the response of the protection system to the SPG fault can be followed by observing the status of the CBs and the evolution in time of I_0/I_1 ratio for all relays.

In both situations, the SPG fault occurs at 5.1 s after the start of simulation and all relays detect a significant increase of the magnitude of I_0/I_1 ratio caused by the presence of the fault. As a result, *CB6* is opened after 0.1 s from the fault inception and shortly thereafter the ratios seen by *R*3, *R*4, *R*5 and *R*6 are zero again because the fault current does not follow their path anymore. However, the magnitude of I_0/I_1 ratio seen by *R*1, respectively, *R*2 are still significantly greater than zero, due to the fact that the entire fault current flows now through the CTs associated with

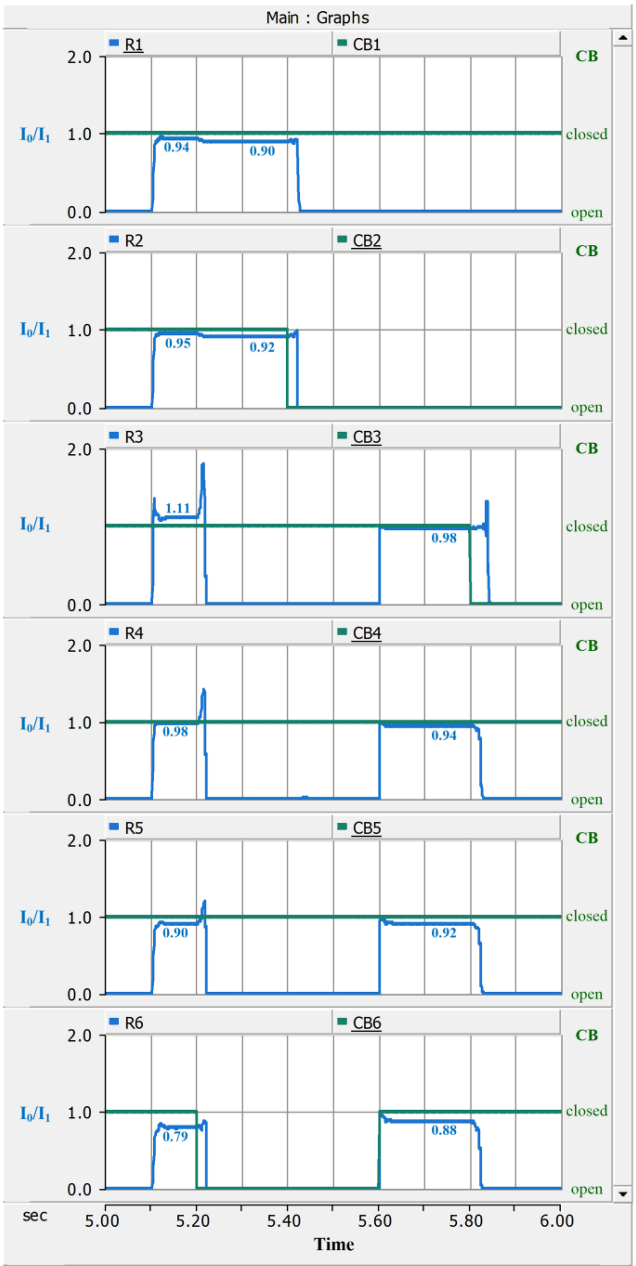

Fig. 5 *Operation of the proposed protection in the case of a bolted SPG fault applied on cable 2 when the test MV microgrid is grid connected*

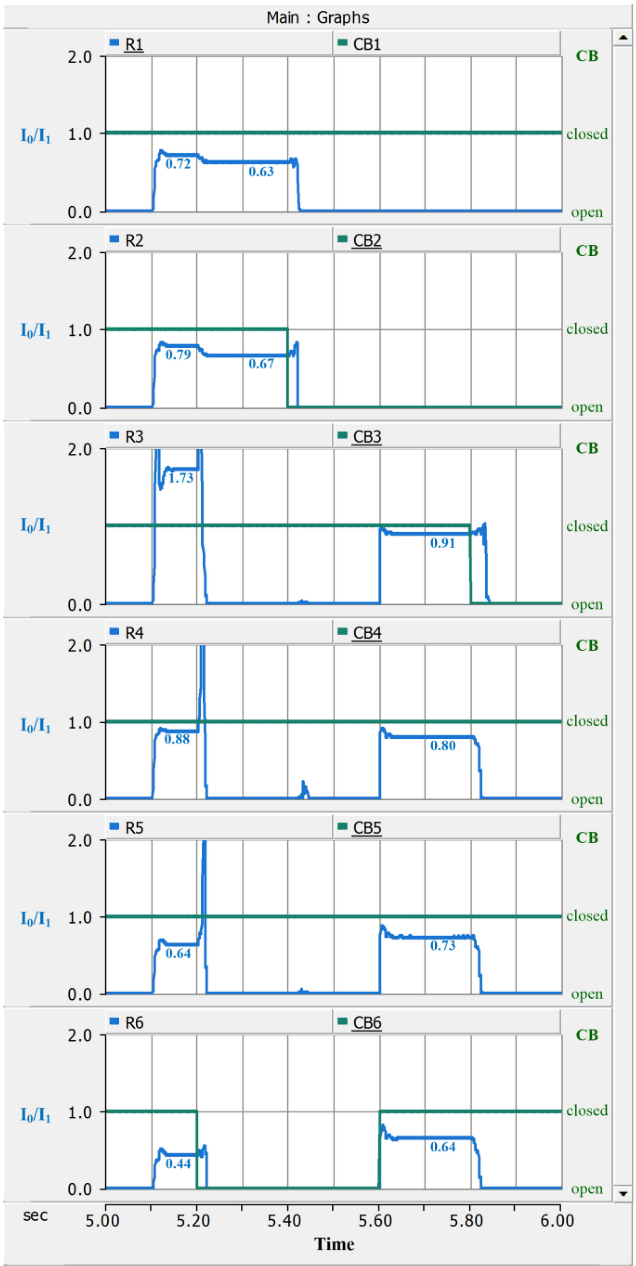

Fig. 6 *Operation of the proposed protection in the case of a bolted SPG fault applied on cable 2 when the test MV microgrid is islanded*

these relays, with the highest magnitude of I_0/I_1 ratio noticed by $R2$: 0.92 in grid-connected mode, respectively, 0.67 in islanded mode. The protection system detects correctly that $R2$ is the closest relay to location of the SPG fault, which causes the tripping of $R2$ after 0.2 s and opening of $CB2$, thus clearing the fault temporarily. $CB6$ is reclosing after another 0.2 s and the fault is re-energised, which causes a significant increase of the magnitude of I_0/I_1 ratios seen by $R3$, $R4$, $R5$ and $R6$, as the fault current flows now through the CTs corresponding to these relays. The SPG fault is cleared by the relay that sees the highest magnitude of I_0/I_1 ratio, which is $R3$ in this case: 0.98 in grid-connected mode and 0.91 in islanded mode. Consequently, the SPG fault is cleared in 0.7 s after its inception by the opening of $CB3$. As expected, the faulted section of the feeder is disconnected in the end by the opening of $CB2$ and $CB3$, so the protection system has worked correctly for the considered faults.

Similar results are obtained for other SPG faults, applied on bus bars or other cables of the test MV microgrid. In each case, only the faulted section of the feeder is disconnected from the network. Simulation results prove that the protection scheme discussed in this paper is able to clear the SPG fault selectively in the test MV microgrid in both grid-connected and islanded mode. Moreover, the variability of the available short-circuit power does not affect significantly the proposed protection scheme, as Figs. 5 and 6 show.

5 Conclusion

Variability of the available short-circuit power causes various protection problems in distribution feeders, protected mainly by OC relays. These problems are more severe in microgrids, which are characterised by larger variations of the available short-circuit power, as they can operate in a grid-connected or islanded mode. Unlike other authors who suggest utilisation of various adaptive protection techniques to mitigate these protection issues, this paper proposes a different approach, in which protection is designed so that it does not need to be adaptive. The proposed relays do not operate directly on fault currents, but rather on ratio between the zero sequence and positive sequence of the fault currents. The introduced ratio does not vary significantly with the fault level changes; hence the proposed protection system does not need to be adaptive to network conditions. Coordination of the protection relays requires communication, which may be needed anyway in a microgrid for control purposes. The new method of protection can be applied in loop feeders, as shown in this paper. Also, the simulations realised in PSCAD prove the effectiveness of the proposed protection scheme in the detection of the SPG faults in closed-loop feeders with variable short-circuit power.

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